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AVIATION RESEARCH LABORATORY

INSTITUTE OF AVIATION
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

TECHNICAL REPORT

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HOW BIG THE MOON, HOW FAT THE EYE ?

STANLEY N. ROSCOE

ARL-77-9 AFOSR-77-8
JUNE 1977

PREPARED FOR
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
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Shifts in the apparent size and distance of real objects viewed binocularly and monocularly and of objects viewed indirectly through imaging displays are accompanied by shifts in visual accommodation distance. It is hypothesized that relaxation of accommodation toward the intermediate resting position in the absence of adequate textural cues to distance attenuates the size of the projected retinal image of more distant objects, thereby causing reductions in apparent size or increases in apparent distance, including certain types of optical illusions.

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How Big the Moon, How Fat the Eye?

Stanley N. Roscoe

University of Illinois at Urbana-Champaign

Abstract

Shifts in the apparent size and distance of real objects viewed binocularly and monocularly and of objects viewed indirectly through imaging displays are accompanied by shifts in visual accommodation distance. It is hypothesized that relaxation of accommodation toward the intermediate resting position in the absence of adequate textural cues to distance attenuates the size of the projected retinal image of more distant objects, thereby causing reductions in apparent size or increases in apparent distance, including certain types of optical illusions.

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BACKGROUND

During the late 1940s and early '50s, I frightened almost everybody at the University of Illinois airport by conducting a series of experiments in which I had pilots landing an airplane by reference to a periscopic image projected onto the back surface of a small screen installed above the instrument panel of an airplane with an aluminum windshield (Figures 1 and 2). The operation was successful, and nobody died, but accurate landings were made consistently only when the periscopic image was magnified by about 20 to 25 percent. When the image was not magnified, pilots tended to overshoot, round out high, and land hard (Roscoe, 1948; 1950; 1951; Roscoe, Hasler, and Dougherty, 1966).

In defense of my doctoral thesis, I was unable to explain this curious though statistically reliable finding. The physiologist on my examining committee, a German named Steggerda who had a great affection for von Helmholtz, speculated that the biased judgments of size and distance might be associated with the convergence of the eyes or their accommodation to the 15-inch distance of the periscope screen. Despite my inability to evaluate this speculation at the time, my thesis was accepted; I became an instant expert and soon thereafter a consultant to the Air Force and industry, who consistently ignored my consultation and proceeded to build and test millions of dollars worth of flight periscopes with a magnification factor of 1.0.

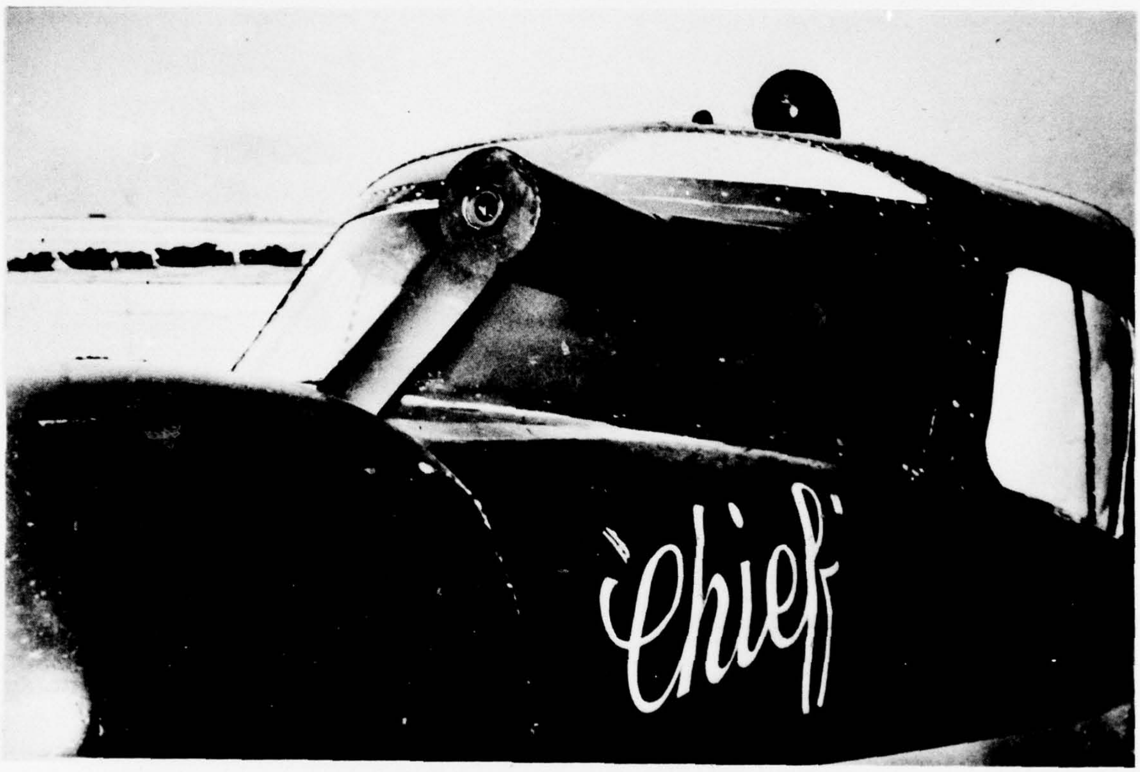

Figure 1. A Cessna T-50 airplane with an experimental projection-type periscope installed through an aluminum windscreen section.

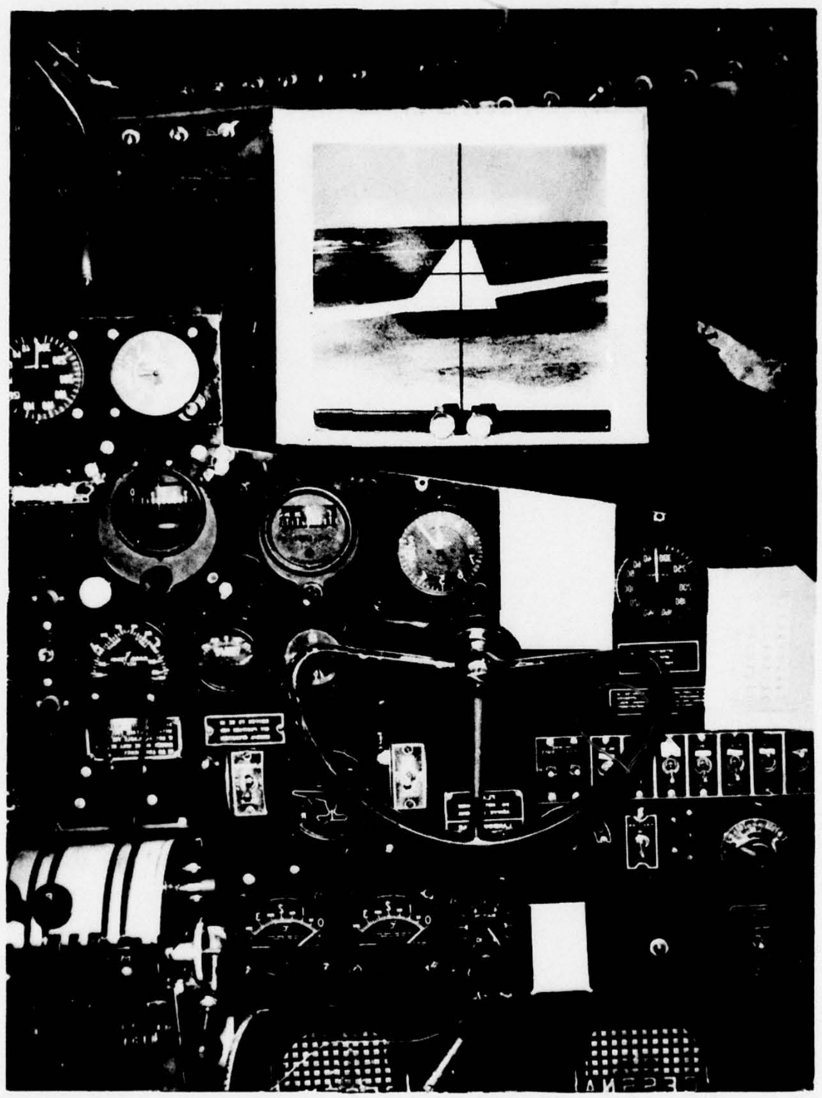

Figure 2. An image of an airport runway as it appeared to the pilot on the projection screen of the flight periscope mounted above the cockpit instrument panel.

On one occasion I failed to persuade a General not to attempt to land an F-84, equipped with one of these periscopes, on the small Republic Aircraft Corporation airport at Farmingdale, Long Island. On his way to takeoff position, he went off the end of the taxiway into the grass, and on landing he badly overshot the aimpoint, landed two-thirds of the way down the short runway, overran the pavement, and ended up in the boondocks near the boundary fence. A subsequent lengthy series of landing trials at Edwards Air Force Base, with larger and larger periscopes of greater and greater optical quality and cost, were aptly characterized by local natives as "controlled crashes." No airplane designed to be flown by periscope has ever been produced.

More than 20 years later, in April, 1976, an American Airlines Boeing 727 overshot its landing aimpoint, landed two-thirds of the way down the short runway at St. Thomas, Virgin Islands, overran the pavement, and ended up a flaming shambles between a service station and a Bay Rum warehouse. Thirty-five passengers and two cabin attendants were killed, and the National Transportation Safety Board found the cause of the accident to be "pilot error." Unfortunately the term "pilot error" does not explain what caused the accident; what is needed is an explanation of what caused a skilled pilot to err on this occasion, under clear, daylight conditions similar to those encountered during the 154 landings he had previously made on the same runway without incident.

It would be slanderous to suggest, or even imply, that this pilot's tragic defection was due to lack of ability, indifference to safety, or worse yet, intention. Nevertheless, in the investigation that followed, the possible relationship between the periscope studies of the 1950s and unusual events immediately preceding the final approach to landing at St. Thomas in 1976 was discounted by the NTSB, as indeed it was by the surviving flight crew themselves. The occurrence of these fully documented events was not mentioned in the NTSB's (1976) official report of their investigation and findings. Stripped of details, the following facts were available from various sources of evidence.

Three minutes before the landing, immediately preceding the final approach, all three of the flight crew verbally expressed pain (and temporary deafness in the case of the Captain) caused by a malfunction or possibly mismanagement of the airplane's pressurization system and a subsequent rapid increase in cockpit and cabin pressure. A slight departure from the planned descent path was requested, approved, and executed. Neither the Captain nor the First Officer was able to see the visual approach guidance lights although clearly visible. Both the Captain and the First Officer, and qualified outside witnesses, judged the airplane to be "in the slot" and expected the landing to be normal.

A formal report submitted by the Allied Pilots Association (1976), pilots of American Airlines only, called the attention of the NTSB to a series of psychophysiological experiments conducted at NASA's Ames Research Center in which:

- Clark, Randle, and Stewart (1975) found that the eyes overaccommodate in response to strong and unusual vestibular stimulation, such as whole-body rotation, and similar effects have been associated with painful and emotion-provoking stimuli, such as "going to the dentist," and threatening or abusive verbal attacks.
- Roscoe, Olzak, and Randle (1976) found that shifts in the apparent sizes of discs were systematically associated with shifts in visual accommodation.
- Palmer and Cronn (1973) found that pilots tend to overshoot, round out high, and touch down hard on simulated landings made using a computer-generated visual display system, and Randle, Roscoe, and Petitt (in press) have subsequently found that the eyes do not accommodate accurately to such displays.

Recognizing that correlations may be coincidental and do not necessarily indicate causal relationships, it is clearly possible that the rapid cockpit pressurization and consequent extreme pain to the flight crew caused their eyes to overaccommodate, blurring their vision and causing the runway to appear farther away and higher relative to the wheels of the airplane than it actually was, thereby causing the pilot to level off high and fail to touch down where he expected to. Neither the NTSB nor the scientific community should discount the possibility that vestibular-oculomotor-perceptual interactions were contributory to the pilot's "error" at St. Thomas (Roscoe, 1976).

A SCIENTIFIC MYSTERY

Bias errors in depth discrimination have been discovered independently by designers of submarine periscopes, tank periscopes, aircraft periscopes, laboratory microscopes, "one-power" scopes for shotguns, helmet-mounted CRT displays, and computer-generated imaging systems. In each of these cases, the optical systems must be compensated by providing a magnification ranging from 1.2 to 1.5 to cause objects to appear at the same distances as when viewed by the naked eye. Although the correction needed for any given system, and in fact for each individual using a system, can readily be established by a simple experiment, the causes of the constant perceptual errors are a scientific mystery, as is the identity of the independent variables that control their magnitude.

In my initial search for the culprit who was breaking the law of size constancy, I soon became convinced that the prize suspect, the oculomotor adjustment of accommodation, had generally been overlooked or inadvertently covered up by investigators of optical illusions, the projection of afterimages, and the size-distance paradox. In virtually every case in which visual accommodation data had been introduced as evidence, the crime was committed indoors, with actual viewing distances seldom greater than six meters and usually not more than four. In frequent testimony in which accommodation was reported to have been either manipulated or controlled, there was no actual measurement of accommodation (e.g., Hollins, 1976).

Until recently it was generally believed, and many textbooks still stipulate, that the resting accommodation position, or dark focus, is at optical infinity, when in fact it is at about arm's length for most people (Leibowitz and Owens, 1975; Leibowitz, Hennessy, and Owens, 1975; Malstrom and Randle, 1976). I could find no case in which accommodation had been measured objectively while the victims of optical illusions were making judgments of the sizes of such distant objects as the sun or moon. And yet, the exposé of the complicity of accommodation in the distortion of perceived size reported by von Helmholtz in 1867 is still unrefuted (Biersdorf and Baird, 1966).

As recently as 1971, Hennessy and Leibowitz, suspecting that "scope viewing errors," or "instrument myopia," as manifestations of mis-accommodation, might be influenced by the distances to objects in the peripheral as well as the foveal visual field (also see Hennessy, 1975). In their clever investigation, accommodation was manipulated systematically and measured quite accurately, but the distances involved were limited by the length of the room, and the experiments did not involve judgments of sizes. Combined with the discovery of the intermediate resting position of accommodation and the tolerance of the visual system to out-of-focus images, this finding suggests a possible explanation for a variety of perceptual mysteries.

The effects on size and distance judgments of various reductions of the visual scene have been studied independently, and several theories have been put forth, but there is no comprehensive explanation of the effects observed. Holway and Boring (1941) measured departures from

size constancy of judgments of discs subtending a constant visual angle of 1° viewed from varying distances with successively reduced visual surroundings; the greater the cue reduction, the greater the reduction in apparent size with increasing distance, as shown in Figure 3. Furthermore, whereas monocular judgments with unrestricted viewing conditions obeyed the law of size constancy almost perfectly, binocular judgments yielded increasing overestimations of size with increasing distance.

Holway and Boring attributed this curious finding to a "space error," thereby replacing one mystery with yet another; to date no one has discovered what a "space error" is. But the "space error mystery" is not alone. The apparent size of projected afterimages is also attentuated by reductions in texture and other distance cues visible in the background (Young, 1952), as is the shift in the apparent size of the sun or moon viewed near the horizon and overhead. Kaufman and Rock (1962) accurately measured the magnitude of the "moon illusion" as a function of the textural distribution and various geometric cues to distance in the visual scene, examples of which are illustrated in Figures 4 and 5.

From these examples it can be seen, first, that the apparent size of the moon increases as the actual distance to the visible horizon increases and, second, that the apparent size of the moon decreases when the scene is inverted (a fact well publicized by Boring), thereby apparently reducing the textural cues to distance in the lower half of the visual field (the upper half of the retina) with possible relaxation of accommodation toward the intermediate resting position. Kaufman and Rock explained their beautiful

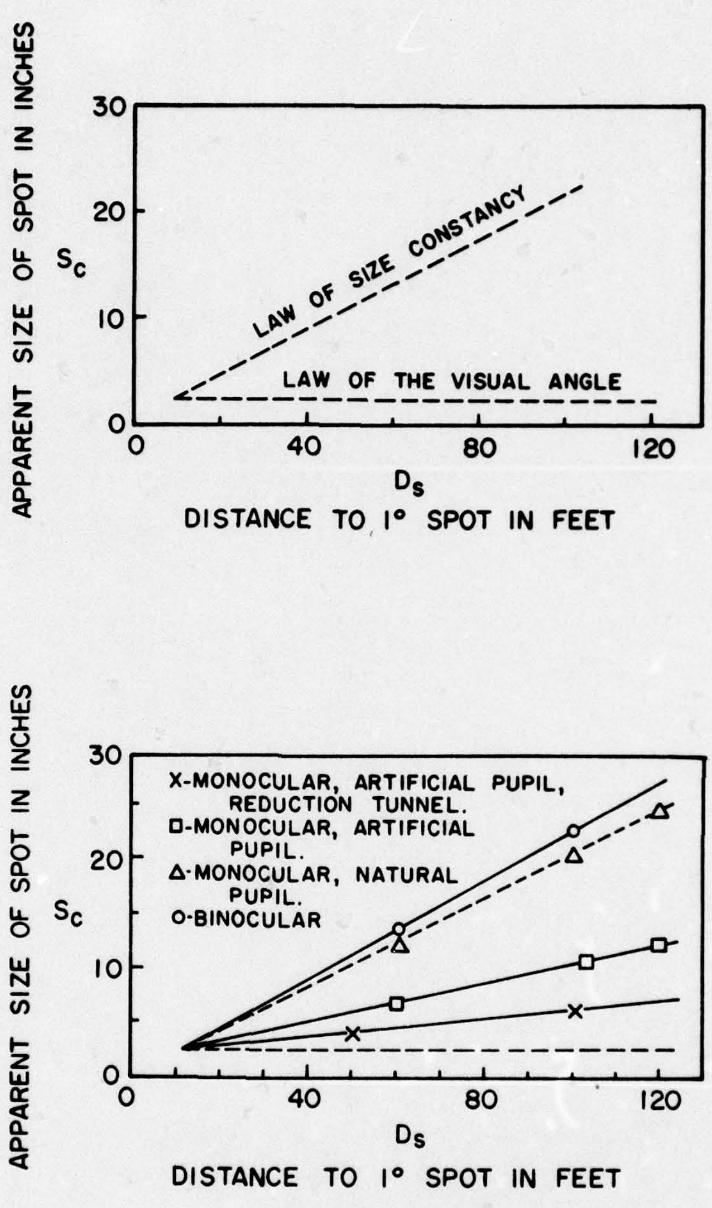

Figure 3. Perceived size as a function of depth cues: The upper diagram shows the apparent size of objects that subtend the same visual angle in accordance with the law of size constancy and on the basis of visual angle alone; the lower diagram shows the data obtained by Holway and Boring (1941) under various viewing conditions.

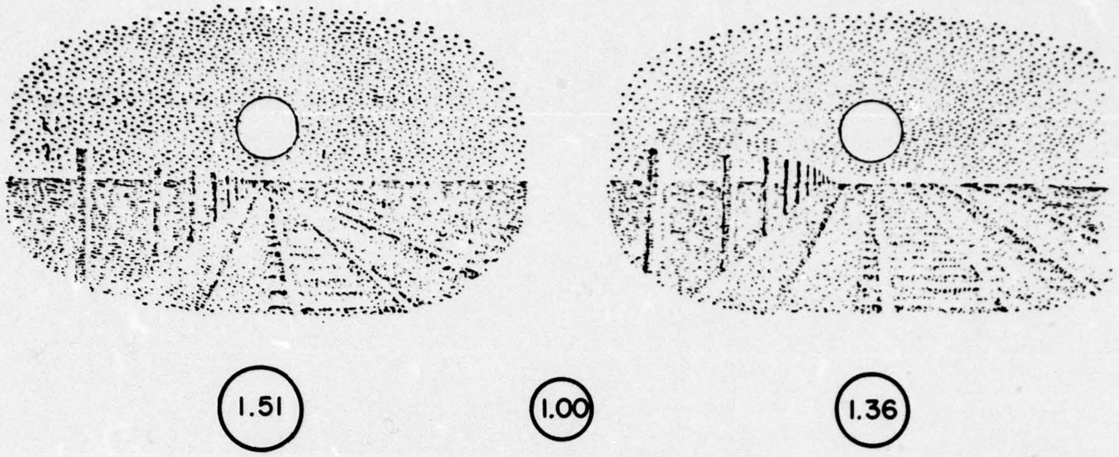

Figure 4. EFFECT OF DISTANCE was tested by comparing two horizon moons with a zenith moon. One horizon moon was placed where the visible horizon was far off (left); the other was over a nearby horizon (right). The illusion varied reliably with distance. (The railroad tracks, added here to emphasize the difference in distance, were not actually in the experimental scene.)

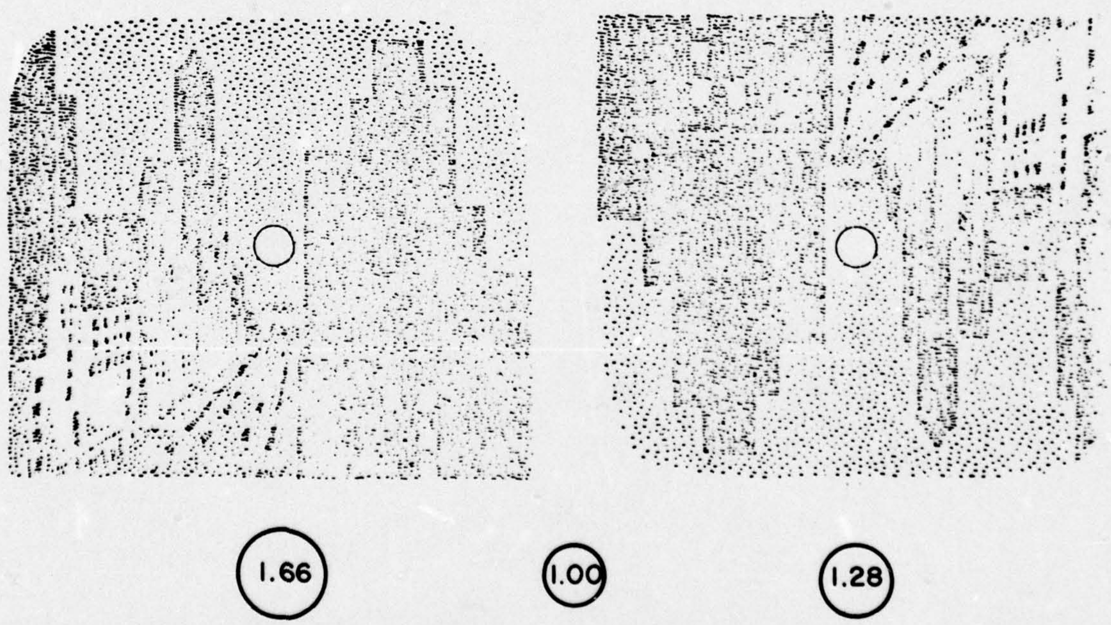

Figure 5. IMPRESSION OF DISTANCE is known to be lessened by inversion of a scene. Two horizon moons were compared with a zenith moon. In one case the horizon moon was seen normally between tall buildings; in the other case the skyline was inverted by a prism. The moon illusion was reliably smaller in the case of the inverted skyline, indicating the greater involvement of the lower half of the visual field (upper half of the retina).

experimental data by stipulating that the moon on the horizon looks larger than the moon overhead because it appears to be farther away.

Once again one mystery had been substituted for another, and when Kaufman and Rock attempted to explain why the moon on the horizon looks farther away, their explanation was not supported by all the admissable evidence; generally observers report that the moon on the horizon appears closer as well as larger than the moon overhead, an example of the size-distance paradox. Although the Kaufman and Rock explanation is unsatisfactory as stated, it might nonetheless be close to the truth if "distance of accommodation" were substituted for "apparent distance."

Throughout the literature of vision research may be found additional examples of unexplained experimental findings and assorted "optical illusions" that may be related to the observations made by Wheatstone (1852) and Helmholtz (1867/1962), and recently verified experimentally by Biersdorf and Baird (1966) and by Leibowitz, Shiina and Hennessy (1972), that the apparent size of an object changes with shifts in the distance to which the eye is accommodated.

The phenomenon can be illustrated by any one of several simple experiments. For example: close one eye, focus your open eye on your thumb held at arm's length, observe a more distant object such as a window or a picture on the wall, and while continuing to focus on your thumb, draw it toward you and observe the change in the size of the window or picture. Better yet: look at the moon through a peekhole through your fist, alternately closing and opening the other eye.

Not only can the moon on the horizon be made to appear smaller, but also the moon overhead can be made to vary in size as well.

It occurred to me that the distance to which the eyes accommodate when one is closed or occluded might be a compromise between the tendency of the open eye to respond to the visual scene and the pull of the closed eye toward the resting position. If this proved to be the case, the shift in the perceived size of objects between binocular and monocular views observed by Holway and Boring and many others might be explained.

Last year, Lynn Olzak, Bob Randle, and I conducted an experiment at NASA's Ames Research Center in which visual accommodation was measured continuously while subjects viewed discs that subtended a constant 3° angle at distances ranging from 1/4 to 4 meters, with and without the distance cues provided by a sometimes visible textural gradient (Roscoe, Olzak, and Randle, 1976). Shifts from binocular to monocular viewing were accompanied by shifts in accommodation, either inward or outward, toward an intermediate resting distance of about one meter (1.13 diopters, on average). This finding is illustrated in Figure 6. The reliable inward shifts from the most distant targets at 4 meters were accompanied by reliable reductions in apparent size (Figure 7).

The presence of a prominent horizontal textural gradient, as opposed to a textureless darkened visual surround, tended to inhibit the shift in accommodation toward the resting position when one eye was occluded; the sparcer the cues to distance, the less accurately the eye

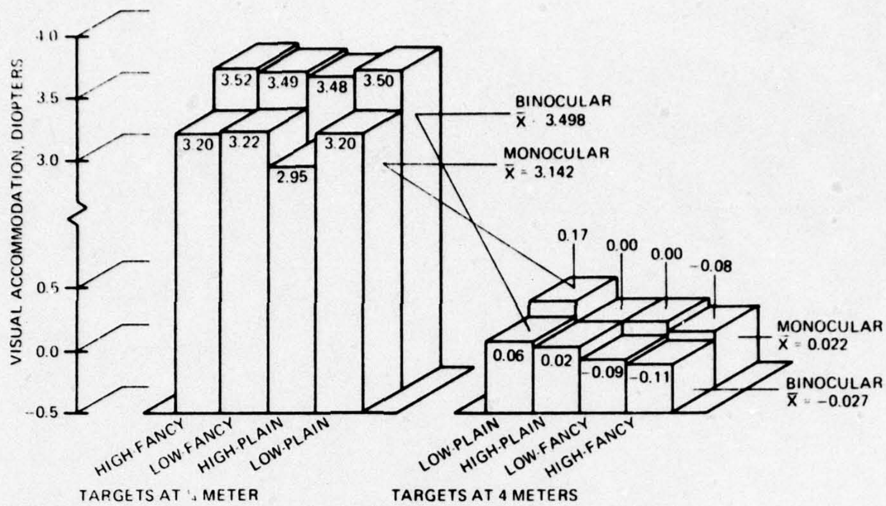

Figure 6. Mean accommodation levels to Plain and Fancy 3^{o} targets viewed binocularly and monocularly at 1/4 and 4 meters under High and Low ambient illumination.

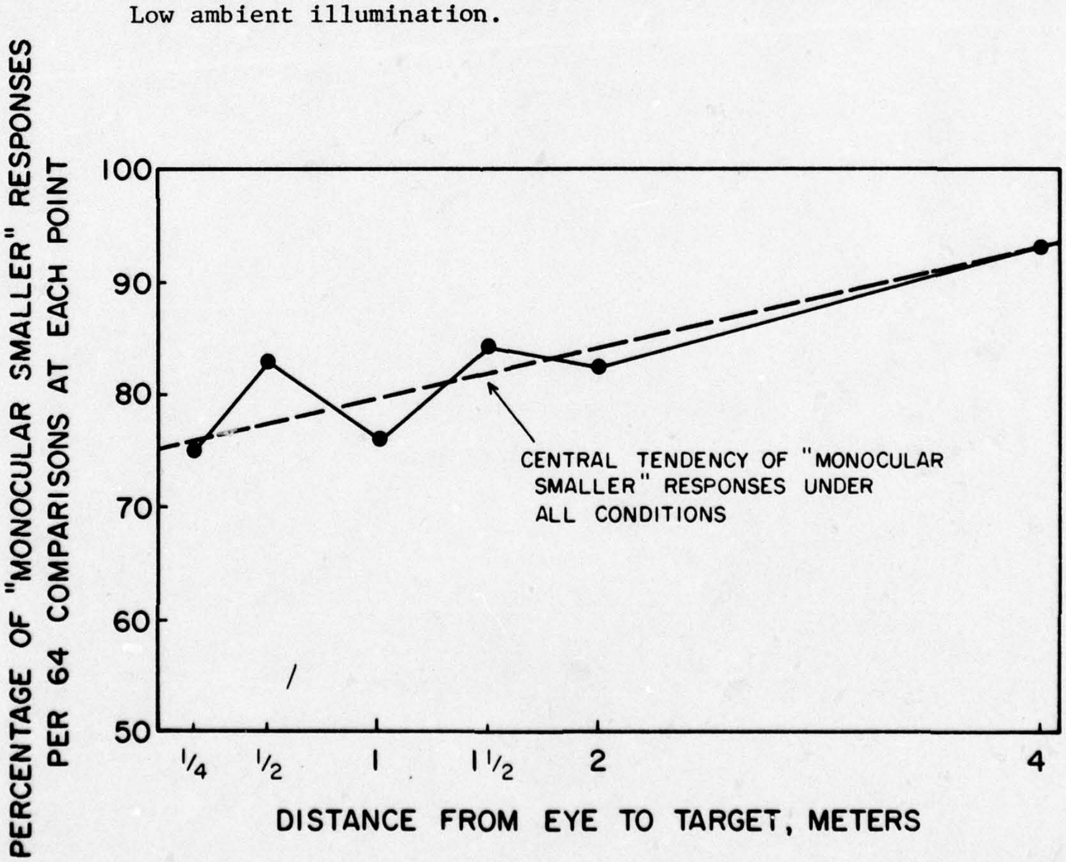

Figure 7. Percentage of "Monocular Smaller" responses in judgments of relative sizes of discs viewed binocularly and monocularly as a function of viewing distances ranging from 1/4 meter to 4 meters (averages for Ascending and Descending series, Plain and Fancy targets, High and Low ambient illumination).

accommodates either outward or inward from its intermediate resting position toward the actual distance of the target. Furthermore, the absence of a visible textural gradient was accompanied by a greater proportional reduction in the binocular to monocular apparent sizes of the two discs presented at distances beyond the resting accommodation position of most subjects.

As in the case of the Holway and Boring studies, the magnitude of the shift in apparent size from binocular to monocular viewing increased with distance, although the range of viewing distances investigated was much smaller than that studied by Holway and Boring. Contingent probability analyses of the reliability of the shifts in accommodation toward the resting position and the associated predicted shifts in apparent size are summarized in Tables 1 and 2; the greater the distance, the more reliable the shift in apparent size.

Although the coincidence of inward shifts in accommodation and "Monocular Smaller" judgments was quite consistent for the more distant targets, the pattern was not consistent at the nearer distances where binocular cues of convergence and disparity increasingly confound the issue. However, by the insertion of an artificial pupil in front of the eye used for monocular viewing (and for the measurement of accommodation), the accommodation of that eye could lapse further toward its resting position without causing a blurred image and thereby allow a clearer comparison of the effects of shifts between monocular and binocular viewing (with the view of the second eye unobstructed).

TABLE 1. Summary of Contingent Probability Analysis of Shifts in Accommodation Toward the Mean Resting Position (1.133 Diopters) when One Eye Was Covered (Chance Probability of Contingency = 0.50).

SHIFT	DISTANCE TO TARGET, METERS					
	1/4	1/2	1	1-1/2	2	4
Toward RP	100	87	55	71	79	79
From RP	28	41	73	57	49	49
Chi^2	39.38	15.82	—	—	6.57	6.57
p	<0.001	<0.002	n.r.	n.r.	<0.05	<0.05

TABLE 2. Summary of Contingent Probability Analysis of Predicted Judgments of Relative Size with Corresponding Shifts in Accommodation (Chance Probability of Contingency = 0.25).

PREDICTED CONTINGENCY	DISTANCE TO TARGET, METERS					
	1/4	1/2	1	1-1/2	2	4
Supported	28	15	29	46	49	57
Not supported	100	113	99	82	79	71
Percent support	22	12	23	36	38	45
Chi^2		11.34		7.59	11.34	25.01
p	n.r.	<0.002	n.r.	<0.01	<0.002	<0.001

Table 3 shows the data obtained for 12 of the original 16 subjects who were tested on near (¼-meter) and far (4-meter) targets both without and with a 1-mm diameter artificial pupil placed 8 cm from the entrance plane of the left eye. The data for the two viewing conditions are not directly comparable in terms of absolute values in that the experimental procedures were necessarily somewhat different. Nevertheless, the two sets of data allow comparison of the relative effects of binocular versus monocular viewing both without and with the artificial pupil in front of the "monocular" eye.

The arrows in Table 3 indicate the shifts in accommodation toward the intermediate resting position from binocular to monocular viewing, and the plus-signs indicate coincidence of positive accommodation shifts and "Monocular Smaller" judgments, or conversely, negative accommodation shifts and "Monocular Larger" judgments. The introduction of the artificial pupil clarifies the relationship: for the 4-meter target, the coincidence is virtually perfect, 23 of 24 cases in agreement; for the ¼-meter target, accommodation shifts in the predicted direction 9 times in 12 under both light and dark ambient illumination, but only in the dark is there evidence of a trend toward "Monocular Larger" judgments with outward shifts in accommodation (9 in 12 cases, $p < .10$).

In addition to the fact that correlations do not guarantee causal relationships, these findings are equivocal because of the confounding of shifts in accommodation, which were measured, with shifts in convergence

TABLE 3. Shifts in Measured Visual Accommodation and Judgments of the Relative Size of Three-Degree Discs, Viewed Monocularly (M) and Binocularly (B) at Distances of 25 cm (4.00 diopters) and 4 m (0.25 diopter) under Normal Room Lighting (Light) and Reduced Illumination (Dark), Without and With an Artificial Pupil in Front of the Left (Monocular) Eye.

	Distance to Target Disc											
	25 cm (4.00 diopters)						4 m (0.25 diopter)					
	Dark			Light			Light			Dark		
S	B		M	B		M	M		B	M		B
	Without Artificial Pupil											
1	4.26	→	4.13	3.67		3.72 +	0.76	←	0.34 +	0.00	←	-0.15 +
2	2.89		3.07 +	3.14		3.21 +	-0.66		-0.47	-0.75		-0.73
3	4.50	→	4.49	5.47	→	3.65	-0.87		-0.86 +	-1.08	←	-1.16 +
4	1.74	→	1.20	1.34	→	0.89	-0.86	←	-0.87 +	-0.80	←	-1.06 +
5	2.29		2.77 +	1.90	→	1.48 +	0.34	←	0.02 +	0.48	←	0.01 +
6	3.02	→	2.74	2.07	→	1.93 +	0.84		1.03 +	1.10	←	0.76
7	3.73		3.76 +	3.88	→	3.42	0.52	←	0.45 +	0.74	←	0.48 +
8	5.28	→	3.91	4.39	→	3.43	-0.34		-0.21	-0.36	←	-0.58 +
9	2.44	→	1.86	2.78		3.05 +	0.58	←	-0.40 +	-0.45	←	-1.03 +
10	4.14	→	3.96	4.37	→	4.24	0.91		1.04	1.87		2.17
11	2.67	→	2.56	3.40	→	2.64	0.41	←	0.35 +	0.55	←	0.41 +
12	3.51	→	3.43 +	3.00	→	1.91 +	0.33	←	0.25 +	0.79	←	0.19 +
Mean	3.37		3.16	3.28		2.80	0.16		0.06	0.17		-0.06
	With Artifical Pupil											
1	2.64	→	2.07 +	3.07	→	2.27 +	0.69	←	0.24 +	1.18	←	0.28 +
2	3.70	→	2.81 +	3.88	→	2.50	1.06	←	0.32 +	0.12	←	-0.43
3	3.86	→	2.86 +	4.42	→	1.78 +	0.87	←	0.26 +	-0.21	←	-0.78 +
4	0.26	→	0.17	0.49		0.79	-0.15	←	-0.67 +	-0.58	←	-0.97 +
5	1.86	→	1.51	2.18	→	1.06	-0.12	←	-0.61 +	0.17	←	-0.33 +
6	4.13	→	2.86	4.40	→	3.38	0.07	←	-0.14 +	0.53	←	-0.56 +
7	3.04	→	1.76 +	3.75	→	2.14	1.02	←	0.68 +	0.63	←	0.39 +
8	4.30	→	2.66 +	4.66	→	4.12 +	0.26	←	-0.11 +	-0.10	←	-0.54 +
9	2.18	→	1.83 +	1.71	→	1.07 +	-0.13	←	-1.02 +	-0.08	←	-0.84 +
10	3.13	→	1.94 +	3.95	→	3.15 +	0.58	←	0.06 +	0.22	←	0.02 +
11	2.58	→	2.24 +	3.12	→	2.51	1.73	←	0.35 +	1.25	←	0.45 +
12	3.32	→	1.98 +	3.08	→	1.54 +	0.18	←	0.05 +	-0.33	←	-0.41 +
Mean	2.92		2.06	3.23		2.19	0.51		-0.05	0.23		-0.31

Legend: Arrow indicates that shift from binocular to monocular accommodation is toward intermediate distance. + indicates that a positive shift in accommodation is accompanied by a judgment of "Monocular Smaller" or, conversely, a negative shift by "Monocular Larger."

between binocular and monocular viewing, which were not measured. Furthermore, the accommodation data are not sufficiently clean for comfort, and a few individual data are suspect by inspection. Nevertheless, neither the data nor their implications can be discounted as completely spurious in the absence of better data. In any case, the mystery is not so much how we judge the size and distance of near objects that afford binocular cues as it is how we judge distant objects that provide only monocular cues.

To gain a better understanding of the effects of visual accommodation upon judgments in tasks involving complex, dynamic visual scenes, Bob Randle, John Petitt, and I recently conducted another experiment at Ames Research Center using a Crain-Cornsweet infrared optometer and an experimental night-landing visual display generated by a digital computer (Randle, Roscoe, and Petitt, in press). Professional pilots made judgments of whether they would undershoot or overshoot their landing aimpoint as the computer flew their simulated jet transport on final approaches to the computer-generated airport scene.

Experimental variables included: (1) the magnification of the visual scene, which was varied in five steps between 0.83 and 1.67, (2) the visual accommodation distance induced by five sets of ophthalmic lenses, (3) the actual descent path of the simulated airplane, which included overshoots and undershoots as well as correct landing approaches, and finally, (4) whether the landing scene was presented as a real image viewed directly on a TV monitor or a virtual image produced by a collimating field lens mounted between the monitor and the pilot.

Our first finding was that the eye does not respond obediently to the accommodation distances called for by ophthalmic lenses; the eye is lazy and reluctant to be drawn away from its intermediate resting position. The brain, in turn, seems happy to accept an amazingly out-of-focus image uncritically and, in fact, without conscious recognition that it is out of focus. In response to ophthalmic lenses covering the range from zero to three diopters, the pilots' eyes, on average, accommodated to the virtual and real images over ranges of only 1.27 and 1.46 D, respectively.

When the pilots viewed the collimated virtual images, their judgments of undershoot and overshoot were not systematically related to their shifts in accommodation. Curiously, when the pilots viewed the real images on the TV monitor, their shifts in accommodation induced by the ophthalmic lenses were accompanied by statistically reliable shifts in undershoot/ overshoot judgments, and in the predicted direction. To thicken the mystery, with the introduction of ophthalmic lenses, the typically found need for a 20 to 50 percent image magnification for veridical distance judgments disappeared in this experiment. On balance, although the range of accommodation levels induced was relatively small, the evidence indicates some relationship to apparent distance or size, but the exact nature of the relationship remains unclear.

Nevertheless, although correlation does not necessarily indicate causation, a partial explanation of bias errors in periscopic distance judgments and in judgments of the size and distance of objects presented on TV screens or viewed directly through frames, artificial pupils, or vision reducing tubes, as well as the shrinkage in the projection of after-

images through a telescope, may depend upon the distance to which the eye accommodates under these various viewing conditions. Such a speculation requires experimental verification or refutation, which must be preceded by a consideration of relevant psychophysiological facts.

When images are projected by forward-looking infrared scanners, television, or periscopes onto a screen viewed from a short distance, the eyes converge and accommodate to the near field of the screen, while objects presented thereon may appear to be at greater distances. The interposition of the screen eliminates all uniquely binocular cues except those of constant value associated with the muscular control of the converged eyeballs and absolutely all binocular cues to the distance of individual objects projected onto the surface of the screen. The most naive, intuitive explanation for a change in apparent size of an object is that the size of the retinal image changes.

However, the speculation that changes in the curvature of the crystalline lens of the eye as it accommodates to different distances may actually change the size of the retinal image is contradicted by virtually every textbook on the subject and is offensive to most scientists in the field. All currently accepted schematic models of the reduced eye are based upon a multitude of unsupported assumptions that, if true, would force the conclusion that the changing curvature of the lens does not appreciably change the size of the image projected onto the retina. In a circular fashion, computations based on the reduced eye are now frequently used to "prove" that the size of the projected retinal image does not change with changes in accommodation. In the face of the evidence that perceived size does change (Biersdorf and Baird, 1966; Leibowitz, Shiina, and Hennessy, 1972), it is time to challenge the assumptions of the reduced schematic eye.

HOW BIG THE MOON, HOW FAT THE EYE?

By now the implications of the title of this paper should be evident, if not entirely clear, acceptably credible, or for some, no doubt, emotionally tolerable. What I hope you will accept are the following observations that I hold to be self-evident.

- Current theoretical models of the visual perception of size and distance are essentially descriptive, and as such they may predict but do not explain size-constancy phenomena or illusory departures from size constancy.
- The traditional dependence of investigators upon reduction experiments to isolate the "main" or "pure" effects of individual stimulus and response variables are inappropriate to complex multivariate mechanisms such as the eye and its associated central neural processes in that they preclude the discovery of interactive relationships among oculomotor adjustments and perceptual responses.
- The traditional dependence of investigators of visual perception upon data from a small number of subjects, often as few as one, two, or three, obscures one of the central variables that compounds the mystery, namely, the great variability in the oculomotor and associated perceptual responses of different people. This single defect invalidates countless otherwise potentially meaningful experiments reported in the perceptual literature.

The recent experiments at Ames Research Center mark the beginning of a systematic investigation of the mysterious interactions between visual accommodation and the perceived sizes and distances of objects presented both by synthetic imaging systems and in natural vistas involving great distances.* In studies to date, an optometer has been used to measure the total optical refraction necessary to maintain a focused retinal image of an infrared stimulus pattern as the eye "accommodates" to different distances (Cornsweet and Crane, 1970; Randle, 1971).

What is measured, therefore, is not a single variable but a composite of a number of adjustments, including the changes in the shape of the lens and the stretching and fore and aft movements of the retina, among others even less well understood that are revealed by the typical oscillatory tracings of the optometer's output signal. The outputs of the optometer, when averaged over an interval of 5 to 10 seconds, yield quite reliable discriminations among relative levels of overall accommodation within the ranges of interest to most investigators, generally out to four meters which corresponds to ¼ diopter.

However, because of the inverse relationship between accommodation and distance, as the eyes accommodate to objects at greater and greater

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*This investigation is now being supported by the Air Force Office of Scientific Research.

distances the outputs of an optometer change less and less. For the purpose of maintaining a sufficiently clear retinal image, all distances beyond six meters are considered to be at "optical infinity" in the sense that rays of incoming light from objects at distances beyond six meters are effectively parallel. Thus, with the eyes accommodated to six meters (1/6 D) or beyond, every object thereafter appears in focus.

Despite this simplifying conception of optical infinity, as shown by Helmholtz, the curvature of the front surface of the lens continues to flatten when viewing objects at distances beyond six meters, and this fact is revealed by increases in the size of the "3rd Purkinje image" reflected from the anterior surface of the lens. The ciliary process, a marvelously complex counter-spring-loaded servo that controls the fatness of the lens with antagonistic sympathetic and parasympathetic innervation (Markham, Estes, and Blanks, 1973), provides a range of adjustment beyond the lens curvature associated with optical infinity. Far-point optometer readings of -2D are not uncommon.

In view of the established correlation between visual accommodation and the apparent size of objects at distances between one and four meters, and in view of the continued change in the radius of curvature of the lens when viewing the parallel incoming rays from objects at greater distances, it is my hypothesis that in addition to focusing the images of near objects on the retina, the function of changes in lens curvature for objects beyond a distance at which focusing is critical is to change the size of the projected retinal image. By photographing the 3rd Purkinji images reflected from the front surface of the lens, a measure of accommodation that increases in sensitivity with distance may be obtained, and such measurements may be correlated with the perceived sizes of distant objects.

During a study of "Human Performance in Aviation Systems" for the Air Force Office of Scientific Research, we have developed a modern adaptation of the phakoscope originally invented and used by Helmholtz. The new device, which we call a photophakoscope, allows measurement of changes in the curvature of the front surface of the lens by photographing the reflected Purkinje images from four infrared point light sources. An illustration of the original Helmholtz device is shown in Figure 8, and the relative sizes of the corneal and lenticular reflections from our four infrared point light sources are illustrated in Figure 9.

When I mentioned this undertaking to Joe Wulfeck, for many years President of the Western Division of Dunlap and Associates, I learned that, a quarter of a century ago, he had perfected a system for studying the speed of accommodation by measuring changes in the size of the 3rd Purkinje image using infrared photography. In this small world during all those years, I had neither a need nor the curiosity to read my friend's marvelous doctoral dissertation (Wulfeck, 1952). Our new device, with which we will investigate the relationships between perceived size and distance and the curvature of the lens, embodies several techniques discovered and perfected by Wulfeck.

Our investigation will focus on the perceived size and distance of objects beyond the usual six meters as functions of varying distributions of textural cues in the distant visual field. Ultimately, we will determine the interactions among a large number of stimulus variables embodied in a variety of visual environments that elicit unexplained phenomena. Some are called optical illusions, such as the moon illusion; others are accepted as normal perceptions but remain unexplained, such as the Holway and Boring findings. An adequate theory of size-distance perception must account for

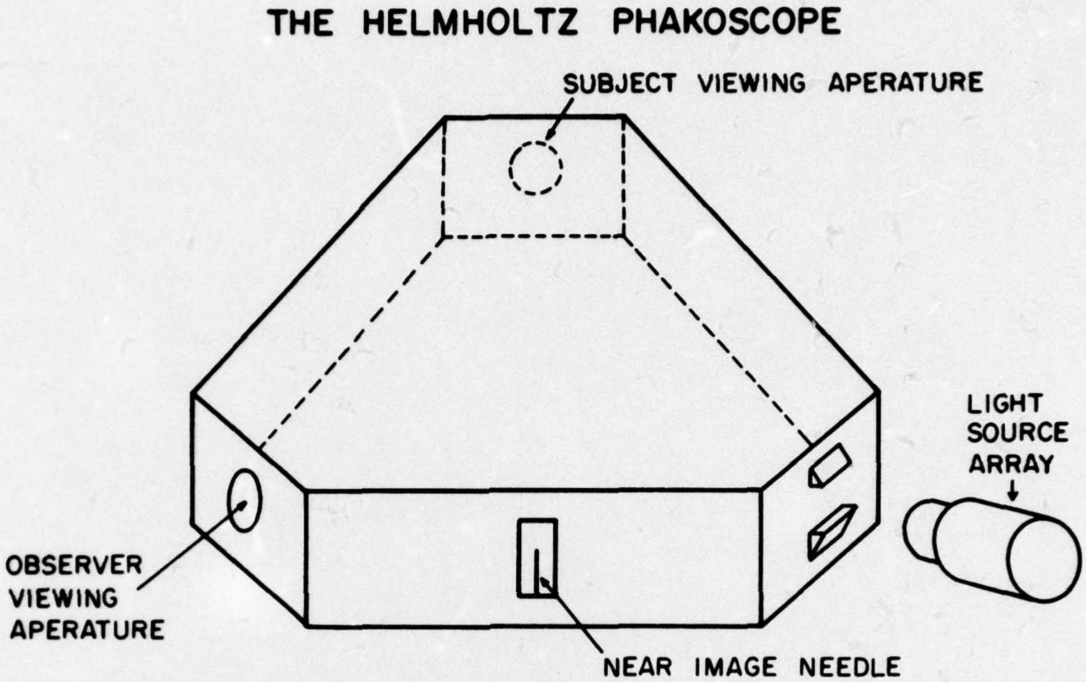

Figure 8. Sketch of the phakoscope Helmholtz used to observe changes in the size of the "3rd Purkinje images" reflected from the front surface of the lens of the eye as a subject views objects at different distances.

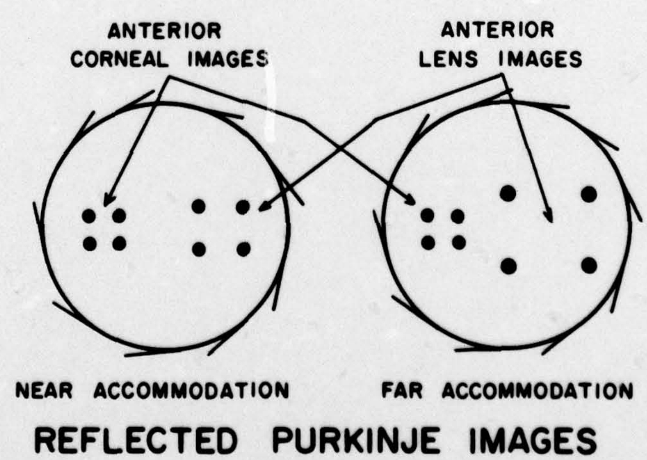

Figure 9. Relative sizes of 1st and 3rd Purkinje images reflected from the cornea and lens, respectively, with near and far accommodation.

all experimental facts associated with judgments of the size and distance of objects, however they may be presented.

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